

Development of Extreme Environment Systems For Seeking out Extremophiles

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I. INTRODUCTION

The last 25 years have witnessed a tremendous change in the way scientists view the viability of lifeforms. We now understand that organisms can adapt to rather incredible environments of pressure, temperature, salinity, pH and assorted adverse chemistries. They establish methods for both surviving and replicating in those harsh conditions. Past efforts to study and understand these organisms have often extracted (or attempted to extract) them from their environment to place them in laboratory settings for examination. Often this approach constitutes too drastic a transition, causing the destruction of the objects of interest. The new task facing extremophile explorers is to find ways to detect and observe these entities in their natural state without excessive disturbances. An associated issue concerns the optimization of observing and measurement time in the hostile environment, especially in the domain of deep ocean hydrothermal vents. A new paradigm driven by cost and temporal-based studies is needed to enable maximum effectiveness of the time at these inhospitable sites. The work in progress by the JPL/Caltech group seeks to enable the informed scientist/engineer to make real-time decisions on the merit of which measurements are to be accomplished immediately and whether the selected site has sufficient merit to continue time-consuming measurements at that location.

II. LAKE VOSTOK, ANTARCTICA: A SMALL-SCALE TERRESTRIAL ANALOGUE TO EUROPA'S OCEAN

Our interest in extremophiles began with the onset of JPL's program to initiate a multi-year, multi-national effort to explore Lake Vostok in Antarctica. The understanding of what a unique domain Lake Vostok really is began to emerge after the publication of the Russian discovery of the Lake by means of seismic and radar soundings [1]. At the international Exploration of Antarctica's Lake Vostok meeting in St. Petersburg, Russia in 1998, we (Carsey and Lane) presented a potential instrumentation scenario for multiple examinations of the Lake and roof-ice regime utilizing a 'cryobot' (Fig. 1).

This vehicle would be placed in a deep, hot water drilled hole that stops a few hundred meters above the ice roof of the Lake. The vehicle is allowed to freeze in place, isolating it from the surface control station and any direct contact with surface

contamination sources. The cryobot, contained in a 'garage' releases a mixture of bactericidal solutions (which might be hydrogen peroxide, for example) and waits in the garage until the detection of microbial contamination drops below some specified limit. Once determined to be adequately sterile, the cryobot is activated and it melts down the remaining ~ 100 m distance to the Lake-ice interface. The cryobot descends by melting ice beneath it and moving downward via gravity's force, with the water refreezing a few meters above the probe as the melted water cools. A variety of scientific measurements are performed along the descent path, including analytical imaging of the adjacent ice with for example Raman and UV fluorescence studies, and examination of the small lozenge of melt water surrounding the cryobot for pH, salinity, and a number of biochemical and electrochemical analyses. The biochemical analyses are important, based upon the work of Priscu, et al. [2]. Once the Lake-roof ice interface is detected by a means such as sonic imaging, the cryobot anchors itself at an appropriate point above the roof and releases a sterile experimental drop package that is tethered by an optical fiber for data return. The drop package slowly descends into the Lake, profiling a number of important chemical species and imaging the zone around the drop package as it descends through the water column.

CRYOBOT AND HYDROBOT IN SITU INSTRUMENTATION

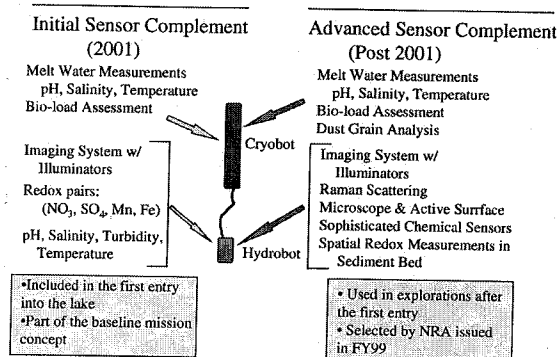


Fig. 1. An instrumentation exploration strategy for Lake Vostok. This was proposed in 1998 to be an aggressive approach to examine the Lake, its ice roof and sediment bed.

The final measurement location is the significantly thick sediment bed whose presence has been established by seismic sounding. All these data are transmitted to the surface station via optical fibers through the 3.8 km long refrozen ice hole. This was our concept for exploration of Lake Vostok and other deep, isolated sub-glacial lakes. The scientific community, through its representatives on SCAR (Scientific Committee for Antarctica Research), deemed the idea very interesting, but refrained from endorsing an active program to enter Lake Vostok until scientific, technical and environmental considerations of subglacial lake exploration could be established and verified. A SCAR Group of Specialists on Antarctica Subglacial Lake Exploration has been formed to address these topics. The work on the vehicle concept and a definition of the engineering aspects of the cryobot continued at a modest pace over the next few years. [3]

II. HYDROTHERMAL VENT INSTRUMENTATION - LO'IIHI 1998

Our first field deployment program occurred in 1998 with the task to image the interior walls of a hydrothermal vent at Lo'ihii, Hawaii. The request came from Prof. McMurtry at the University of Hawaii, who was interested in obtaining confirmation and origin information of visible gelatinous-like material observed emanating from vent throats in hydrothermal vent fields of Lo'ihii. In 1997-8 the reported vent water temperature was $\sim 200^{\circ}\text{C}$, at a depth of 1300m. Although the request seemed straightforward, we knew of no imaging system whose detector was designed to survive and operate at such hot temperatures. In addition, if we considered the standard miniature charge-coupled device (CCD) array detectors or other silicon structure sensors such as charge-injection devices (CID) and CMOS active pixel sensors, they all suffered from the same deficiencies of very high dark current at elevated temperatures with degradation of supporting circuit element piece-parts. Other hydrothermal vent explorations, at the Juan de Fuca ridge and in the East Pacific ridge off the west coast of Guatemala, have measured vent water temperatures of $>350^{\circ}\text{C}$, with at least one location having a temperature of $>400^{\circ}\text{C}$. The task centered on designing a simple system that would be able to image interior walls and yet withstand many minutes of contact with high temperature fluids and severe thermal cycling.

The solution to this particular problem lies in the fact that the vent water generally cools very quickly to the near-ambient cold ocean water temperatures of 4 to 6°C within 20 to 40 cm of the side of the vent plume column or within 60 to 70 cm above the vent hole (for small plumes). We considered standard air-path, re-imaging optical designs but realized that the air column within the hollow shaft we would place into the vent holes would be seriously disturbed by the interior

convection cells driven by the hot end of the probe. Such a disturbance would markedly blur the imaging wavefront. A vacuum pathway, while possibly feasible, would add significant mechanical and thermal isolation complexity to the probe shaft whose outer diameter we were trying to maintain at ~ 4 cm for access to most vent holes.

The implementation approach selected utilized a coherent optical fiber bundle, very much like a medical endoscope. However, the medical systems, though designed for thermal/chemical sterilization, were not designed to survive at temperatures much above 130°C . Several commercial initial fabrication efforts did not succeed, but one 100 cm long coherent optical rod was produced eventually with a usable imaging conduit diameter of 10 mm, which was sufficient to cover an 8 mm CCD detector. The individual fibers in the rod have a core diameter of ~ 2.5 μm with a cladded diameter of ~ 4 μm . This arrangement gave two or more imaging conduits for each CCD sensor pixel (between 8 and 12 μm squares). The meter-long rod was extremely rigid and optical testing showed a very satisfactory coherence between a source image focused on one end and the emergent image at the other end. The remainder of the design required no new technology developments, just care to details of mechanical alignments and efforts to reduce the effects of strong thermal gradients.

Virtually no sunlight reaches depths below 350 to 400 m in the ocean, and inside a vent even the intense lights on a submersible do not provide illumination because most vehicles do not have multi-degree of freedom remotely manipulated arms that contain illumination sources. Even if they did, the geometry of illumination from outside the vent would generally produce extreme shadow regions, resulting in significant difficulty with image content interpretation. The optical system was designed to image the sidewall of a vent at a distance of 2-4 cm from the probe shaft wall as the probe was inserted and moved into the hole or crack. Illumination had to be provided, but small quartz-halogen or xenon lamps, at the probe tip end where the imaging window existed, would also be subjected to the intense heat of the vent fluid. Again we turned to optical fibers as a convenient approach to deliver light. High-intensity red, orange, green and blue LEDs were mounted inside a block of aluminum that contained specially machined conical focusing seats for the LEDs. A ring of four of each color, separately commandable on/off, was mounted in the cold water end of the probe and the light delivered to the hot-tip probe end by sixteen 400 μm core, aluminum cladded optical fibers. The aluminum jacket ensured that no light would leak out of the optical fibers near bend points in the pathway and thus prevent the development of a high intensity scattered light field within the probe's optical housing. A 'spinneret' style plug, machined to provide a pattern of 16 closely packed holes (0.60 mm diameter, each) at an oblique angle to the imaging axis of the probe tip, provided the pathway for the

optical fibers to illuminate the imager's viewing volume. One white light incandescent bulb was included, and its illumination was delivered to the probe tip through the same spinneret plate; it used a 1000 μm core fiber for its delivery through a 1.38 mm oblique hole in the spinneret plate.

The camera, lights and imaging data were controlled by a laptop computer inside the Hawaii Underwater Research Laboratory's (HURL) *Pisces V* submersible. SeaCon connectors interfaced the control and power functions from within the *Pisces V* to the probe that was manipulated and positioned by the *Pisces V* remote manipulator arm. There was insufficient time and no funds to develop a deep ocean titanium structure. The probe shell was fabricated from stainless steel sections, using ultra-high vacuum copper gasket knife-edge technology, in an effort to fabricate the unit on a very tight schedule with very modest funding.

The hydrostatic testing program required for this instrument to be accommodated on the *Pisces V* submersible was delineated by HURL to be 10 pressure cycles to 2250 m pressure depth at a minimum rate of 250 m/min. The final cycle required holding the fully configured shell for one hour at maximum test depth. The entire instrumented probe passed its tests in the laboratory, was disassembled for shipment to Honolulu and rebuilt there. Fig 2. shows the probe during its deployment at Lo'ihi.

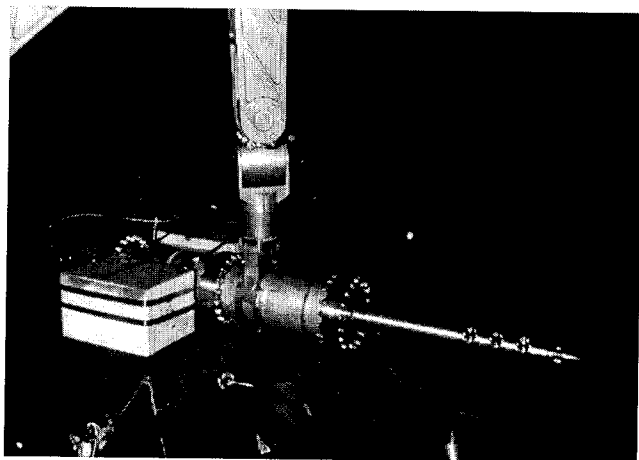


Fig. 2. The Lo'ihi probe during its initial deployment at 1300 m. The *Pisces V* arm supports the midsection of the probe, with foam ballast blocks attached to diminish the effective unit weight. The illumination and imaging ports are seen on the right side of the small insertion shaft.

At depth, two of the 17 optical fiber penetrations through the spinneret plate developed a pinhole leak that filled the probe interior with water after 5 hours of immersion. Subsequent inspection showed that the leaks appeared to be $\sim 1 \mu\text{m}$ cracks in the epoxy glues that held the fibers in the spinneret holes and we surmised that water was forced under external

pressure to creep through the vapor-deposited aluminum outer jacket of these two optical fibers into the probe interior cavity. Nonetheless, we had developed and tested our first deep ocean instrumented package in just six months and had developed a very good understanding of how to proceed with future instrumentation developments.

III. HYDROTHERMAL VENT INSTRUMENTATION – SOUTH PACIFIC 1999

In the year following the Lo'ihi activity, we developed a more advanced titanium probe shell that could withstand full ocean depth ($>8000\text{m}$ pressure), was more easily assembled using multiple o-ring seals and still maintain the capability to have the vent probe end sustain temperatures near 400°C . The shell design used the same basic internal optical configuration developed for the Lo'ihi probe, and incorporated the titanium pressure hull designs of David Copson at the University of Hawaii. This system included imaging, light sources and a first effort at UV-induced fluorescence and spectroscopy. A geometric cartoon is shown in Fig. 3 along with the location of the principal components.

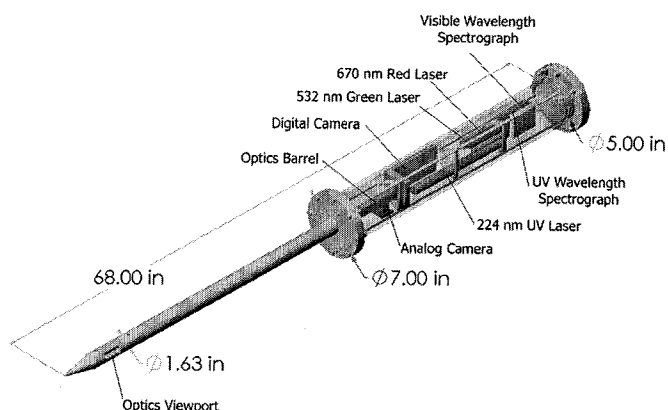


Fig. 3. Component and geometry diagram for the South Pacific 1999 probe.

The side-looking imaging had to be modified to enable a more robust window design that could withstand much greater pressure differentials than that which was part of the Lo'ihi design, which had a limit near 2500 m depth. The window, which needed to be quartz to permit future near-UV imagery of objects, was designed as a conical plug fitted and lapped into a long conical seat. To protect the window from impacts by volcanic rock surfaces when the probe tip was being inserted into a vent hole, the window was moved to be coaxial with the coherent optical fiber imaging rod and located inside the probe's outer 4 cm diameter.

Because the probe was not required to be sterile and free from organic material in its construction, the window seat was lubricated with a thin film of high-temperature, copper-

filled epoxy to provide both an elastomeric pressure seal and the required high temperature survival capability. The side-viewing geometry is achieved by turning the viewing direction from towards the probe tip to the side by a high-efficiency, overcoated mirror housed within the probe barrel near the probe tip (Fig. 4).

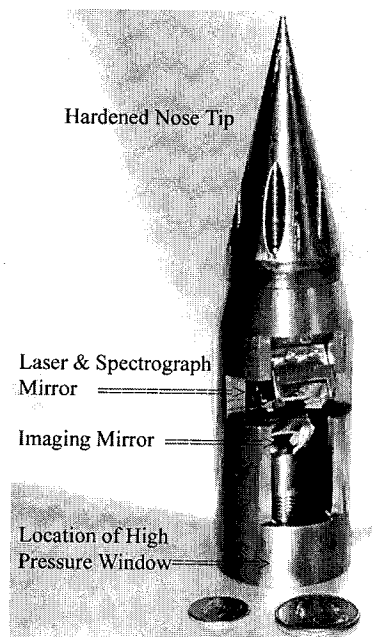


Fig. 4. The Optical Nose Tip. The mirror cell contains two mirrors set on different axes. The imaging mirror is on the central axis facing the high pressure window on the probe shaft. The laser & spectrograph mirror is offset and behind the imaging mirror. Thin Teflon pads cushion the mirrors.

The intensity of illumination on the sidewall surfaces was improved by changing to laser diode sources: a red pair at 670 nm and a single green source at 532 nm. These sources, coupled to optical fibers, provided strong illumination in the imaging volume. In addition to the red and green illumination for the imager, a new technology 224 nm UV laser from Photon Systems, Inc. was included in the probe. This laser was designed to provide fluorescence pumping of any organic material that might be found on the interior walls of the vents or floating in the outward flowing hot water. The imager, restricted by the blue-end response of the silicon CCD detector and only very slightly by the all-quartz optics, could detect fluorescence as short as 400 nm in wavelength.

In an effort to further examine any potential fluorescence and achieve a better understanding of what material might be responsible for any detected signal, an optical fiber coupled spectrograph was included in the payload. A commercial Ocean Optics, Inc. near-UV/green system was modified to fit within the probe's electronic bay housing. Its input fiber was

bundled with the laser illumination fibers, with all of them aluminum jacketed to prevent light scattering from the laser sources into the low-intensity spectrograph input fiber. The full set of optical fibers was epoxied into a special 3 mm sleeve and sealed into the window mount assembly by SeaCon. This design proved to be extremely robust and leakproof. The optical fiber illumination sources and spectrograph shared a second turning mirror in the probe's nosepiece that provided an intersecting volume at a common plane 2 to 4 cm from the side of the probe shaft. Fig. 5 is a picture of the completed probe.



Fig. 5. The completed titanium probe, just prior to attachment to *Nautila*. The electrical connectors are on the far right. A wristwatch in the foreground provides a measure of scale.

The Lo'ihi dive program for which we were developing this second probe was cancelled three months into our development cycle. Through the kind efforts of Prof. McMurtry and Prof. Cheminee at IFREMER (French National Oceanographic Research Institute), we were given an opportunity to join the POLYNAUT '99 campaign with the *Nautila* in the South Pacific. Design changes in the command, control and power circuitry were required to enable the *Pisces V* design to be accommodated within the *Nautila* vehicle. Because we had no explicit knowledge of the sites to be studied, the French engineering staff provided a pressure testing profile that would suffice for all the anticipated locations. The probe shell, window and feedthroughs were subjected to a 10 cycle test with a maximum pressure equal to 8800 m depth on each cycle. No problems arose.

The dive activity was partially successful. The UV laser power supply could not be carried within *Nautila* and had to be encased in its own pressure vessel that was mounted near the ballast tank beneath the *Nautila* external shell. The wiring harness was inspected and checked for continuity a day prior to deployment, but at some time during deployment an electrical connection opened. The UV laser was not functional during the dive. Some imaging data were acquired and recorded. Fig. 6 shows the probe being placed into a vent hole. These data appear to be noisy because of an electrical or RF pickup problem within *Nautila*. Nonetheless the concept of a scientist/engineer actively acquiring real-time in-situ data from a manned submersible was tested and proven to be very valuable.

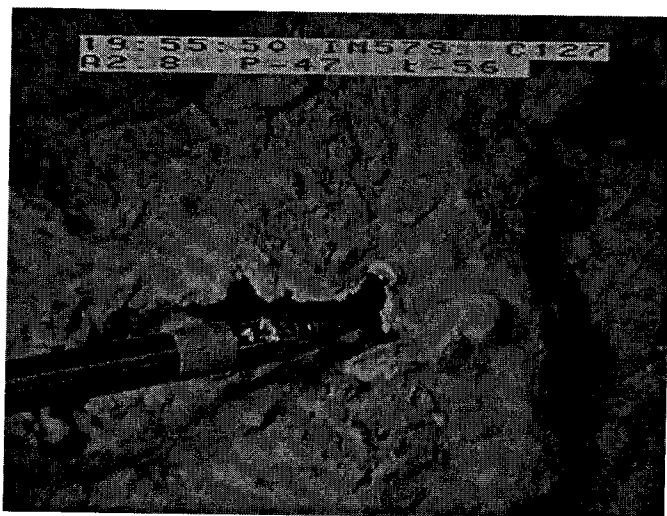


Fig. 6. Probe tip being inserted into a cool hydrothermal vent during deployment from Nautile on the Bounty Seamount. Depth is 580 m. The open mirror cell faces upward in this geometry.

IV. DEEP GLACIAL IMAGING: ANTARCTICA 2000

In preparation for eventual exploration of Europa's ocean and polar cap regions on Mars we developed in collaboration with Caltech another set of instrumentation, the Ice Borehole Camera, that saw its first application in Antarctica in Dec. 2000. The objectives were to observe ice-bed interactions with a downward looking camera, and ice inclusions and structure, including hypothesized ice accretion (freeze-on processes), with a side-looking camera. The real-time data display from both views was used to guide the scientific staff's observational decision process. The effort also served as another stepping-stone in the development of technology to acquire data in extreme ice and liquid environments.

The basal regime of ice sheets and glaciers is of increasing interest. This interest stems from a new appreciation of the role of the rock-ice-water system processes of the sub glacial in the dynamics of ice sheets, the response of (even quite large) ice masses to climate change, and the creation of habitat for a community of chemotrophic microbes thought to contribute to local biogeochemical weathering. Observational work in the basal regime is challenging: the pressures are high, access is difficult, removal of ice samples is cumbersome because the warm ice is not competent, and the process of drilling into the ice alters the environment of interest. In the study for which the Ice Borehole Probe has been designed we address these issues through development of an in-situ deployment strategy which acquires a video record of the ice sheet adjacent to a hot-water drilled hole; this ice has not been significantly affected by the drilling process, either chemically or physically, and considerable information about it can be derived from other optical probes,

e.g. Raman and fluorescent spectrometers, to be developed in future. Additionally, the probe was designed to collect the first visual data set on the interaction of an ice sheet with its bed, in this case a mix of wet and frozen material. This unique inspection of a fundamental geological process is of great interest. Clearly the system-level requirements on a subglacial probe are significant in all areas, including general robustness, high data rates, high pressure, lighting, tether management, and the like. This is the first time that all these matters have been considered in this type of probe.

Deep boreholes were drilled through the Antarctic ice sheet using a proven hot-water jet technology developed by Caltech [4,5,6]. The boreholes were large enough (~17 cm diameter) for the down-hole deployment and safe retrieval of the Probe in the six hour duration before the refreezing process narrowed the hole diameter to a point where removal was impaired.

The Probe system diagram shown in Fig. 7 below gives an overview of the three main segments of the system which was deployed in 2000-01. The power for the down-hole probe containing the cameras, light sources and the communication interfaces is derived from a 300 VDC power source located on the Antarctica surface above the borehole. The high voltage DC is impressed on the copper wire in the tether cable and after resistance losses over the 1500 m length is converted into 5 and 12 VDC busses.

The Probe contains the cameras and associated electronics as shown in Fig. 8. Two CCD cameras are used. A high-quality digital camera (side looking) and a high-resolution video camera (down looking) acquire the images. Low wattage halogen bulbs provide the illumination, with one bulb for the side looking camera and two bulbs for the down-looking camera. Video electrical signal data from the cameras are converted into optical streams and each is sent up separate optical fibers to the surface station. The downward looking camera has only a power-on, automatic operation mode. The side looking camera records internally up to 2 hours of digital video, as well as sending out a real-time, analog video stream. The very high-resolution taped digital images are removed from the Probe when it returns to the surface station. NTSC video-to-analog fiber optic converters send image data through the tether in real time to the surface control station. The side looking camera has a zoom control command function via an optical fiber command line from the surface; hence the scientist/operator can zoom and focus onto interesting objects seen in the real-time stream.

The deployment tether system is a direct copy of reel systems utilized in past years by the Caltech drilling group. The tether that lowers the Probe down through the water-filled ice borehole is wrapped on a spool about 0.9 m in diameter, which holds 1500 m of tether, long enough for the deepest

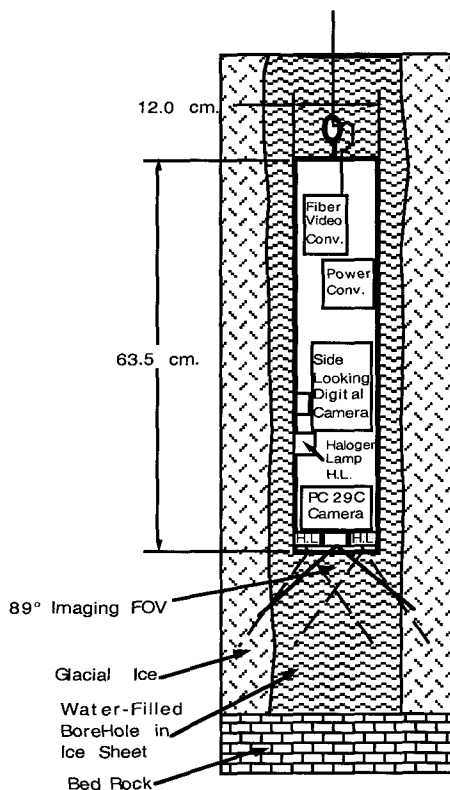


Fig. 7. Diagram of the Borehole Camera functional units and the Camera's geometry in the borehole.

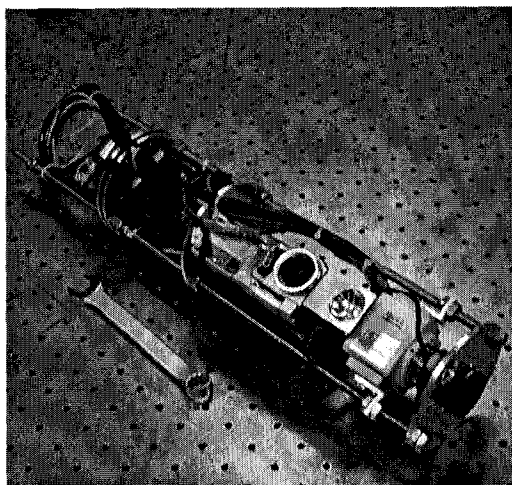


Fig. 8. Interior of Borehole Camera. The sidelooking & downlooking cameras and light sources are in the picture's foreground, with the electronics and optical connections in the background.

glacier study area. The tether is a reliable single cable system that provides data, power, waterproofing, support (strength) members and the structural integrity of all internal elements, all within a cross-sectional 9 mm diameter. The data are transferred along four optical fiber lines and power is

transmitted along two 18 AWG insulated copper wires. The entire unit, cable, spool, motors and sled, weigh ~180 kg. The main spool is rotated with a three-phase AC motor which enables a maximum descent rate of about 1 m/s and a variable speed control enables slow descent or ascent at rates as low as ~4 mm/s.

The surface ground station provides power (110 VAC) for the computer equipment that records and displays image and engineering data, and issues commands to the probe. The two cameras' analog image data are recorded onto digital format recorders to preserve data quality for many replays and the control station computer decodes the probe depth information from the cable reel rotations. All data are time-tagged to enable detailed correlations post-facto. The real-time video display has sub-windows for depth and time to assist the operator in locating unique features. Command transmission for changing zoom view of the side-looking camera occurs from the surface ground station. The highest quality digital images, recorded on DV tape within the side-looking camera, are removed from the probe and camera housing after the probe is returned to the surface station. Time tagging provides a direct correlation between these taped images and the analog real-time recorded images.

The Ice Borehole Camera had a number of deployments in the hot-water drilled holes created by the Caltech Glaciology Group. Side looking images were recorded in 100 m segments from the surface to a maximum depth of ~1250 m. Material trapped in the deep ice was imaged at scales as fine as 100 μ m (Fig. 9). In one of the holes we were able to image the bottom of the glacier from within a small water channel upon which the glacier 'floated.'

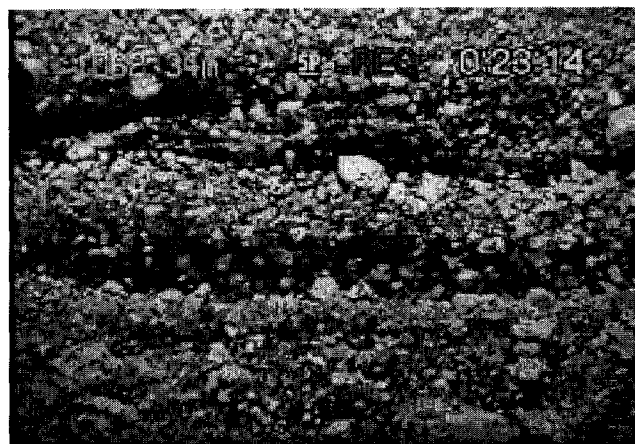


Fig. 9. One side-looking image from the Ice Borehole Camera, taken at a depth of about 1063 m. Accretion of basal ice in the presence of saturated sediments could generate ice lenses of this type. These are a few millimeters in thickness and separation and are composed of gravel. Note the clarity of the ice in the lenses. (Up in the figure is down in the ice.)

A new system is currently in fabrication to allow deeper observations, along with new instruments designed to enhance the capability to seek potential cryo-organisms that can survive in the interstitial water channels found between ice crystals.

V. CONCLUSIONS

We have begun to assemble the instrumentation technologies eventually needed to acquire important scientific information from the cold regimes of Mars, Europa and other outer Solar System bodies. We have demonstrated their use and applicability in terrestrial environments where we are able to test and verify our working hypotheses and concepts, while acquiring scientific information of great general interest. We expect to continue this evolutionary path in order to be ready for major scientific campaigns in the deep ocean and the terrestrial polar ice fields so that we can respond to the future challenge of seeking new scientific discoveries in the Solar System with proven instrumentation capabilities.

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